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Project Title: Developing InSAR capabilities for monitoring episodic subduction zone slip and crustal deformation in western Washington State

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2. Abstract

In this study, we analyze the potential effectiveness of the application of various InSAR techniques to constraining the diverse ground deformation processes in the Pacific Northwest, including tectonic (crustal faults and slow slip events), landslides, and groundwater surface deformation processes. Project deliverables were separated into three main groups of questions. First, how well do models of deformation during ETS events that are generated using independent datasets predict the InSAR measured component of deformation during known slow slip events? To first order, do we expect that deformation during slow-slip events observable with InSAR? What additional constraints can InSAR provide on ETS events and their possible relation to regular earthquakes? Second, how do patterns in the InSAR line-of-sight component of deformation for the Puget Sound lowland relate to mapped fault locations? What kind of deformation exists across mapped faults and is there any evidence for steep deformation gradients that may be related to unmapped faults in the region? Third, how are GPS sites contaminated by localized, short wavelength deformation due to non-tectonic processes?

Our research resulted in one publication (Finnegan et al., 2008) that was the first application of InSAR (InSAR) time series analysis in the Seattle urban corridor. We successfully combined several datasets spanning 1992-2006 and concluded that deformation associated with aquifers and extraction of groundwater dominates much of the short wavelength deformation in the Seattle metropolitan region. Little evidence is found for deformation across mapped crustal faults although we found several linear features in deformation rate maps that may represent unmapped near surface faults. We directly compared InSAR time series results with continuous GPS stations in the Seattle urban corridor and found that the two approaches produce comparable results at the level of mm/yr.

In terms of searching for slow slip events with InSAR, we have attempted to use both conventional InSAR as well as the InSAR persistent scatterers technique (PSInSAR). Forward models based on inversions of GPS observations suggest that between 1 and 2 centimeters of deformation in the satellite line-of-sight is expected to occur during slow slip events. Constraints on the depth extent of slip are very sensitive to the vertical component of the deformation, so accurate measures of vertical deformation such as those that could be provided by InSAR could complement the primarily horizontal observations of GPS. Although we did not identify unambiguous deformation associated with a slow slip event, we found that both conventional InSAR and PSInSAR show promise for detecting slow slip if data acquisitions were made more frequently, particularly at longer radar wavelengths such as L-band. To this end, our USGS project has partly motivated and contributed to the development of a Seattle-Vancouver “supersite” that will provide open access to InSAR and other datasets for this region.

3. Main Body

A. Introduction

This research project was aimed at better understanding earthquake and tectonic processes in the Pacific Northwest using InSAR in three fundamental ways. The three areas of study involved assessment of deformation associated with 1: Potential GPS contamination by non-tectonic processes, 2: Upper crustal faults in the Seattle region, and 3: Episodic Tremor and Slip. We have investigated all three proposed deliverables and assessed the potential for use of InSAR in all three categories. The subsections below lay out in detail our investigation of these three categories.

B. GPS and InSAR in the Seattle Urban Corridor

The extensive and dense vegetation in the Pacific Northwest, as well as the large amount of precipitation, pose great challenges to applying any InSAR technique in the area. We first present results recently published in the *Geophysical Journal International* by Finnegan et. al. [2008] demonstrating that high levels of coherence in the Seattle urban corridor can be effectively used to study local, short wavelength deformation features associated with tectonic processes and variations in groundwater. For this project, 66 acquisitions were acquired from the ASF data facility for the ERS 1/2 tracks 156 and 428 and RADARSAT Finebeam mode. Processing was done using the ROI_PAC software package provided by Caltech/JPL (Rosen et. al. 2004) and unwrapped using SNAPHU (Chen & Zebker, 2002). A spatial averaging filter was applied to the interferograms to reduce noise and then long wavelength signals (>50-100 km) were removed from the unwrapped interferograms to account for uncertainties in satellite orbits.

With the large number of interferograms processed, there were multiple constraints on many of the time intervals between acquisitions. This allows a least squares inversion scheme to be applied to the unwrapped interferograms to solve for the deformation history at any given point. This was done for several locations that coincided with continuous GPS stations, and results from that are shown in Figure 1. Comparing InSAR derived values with GPS serves as an important check on the accuracy of the InSAR time series.

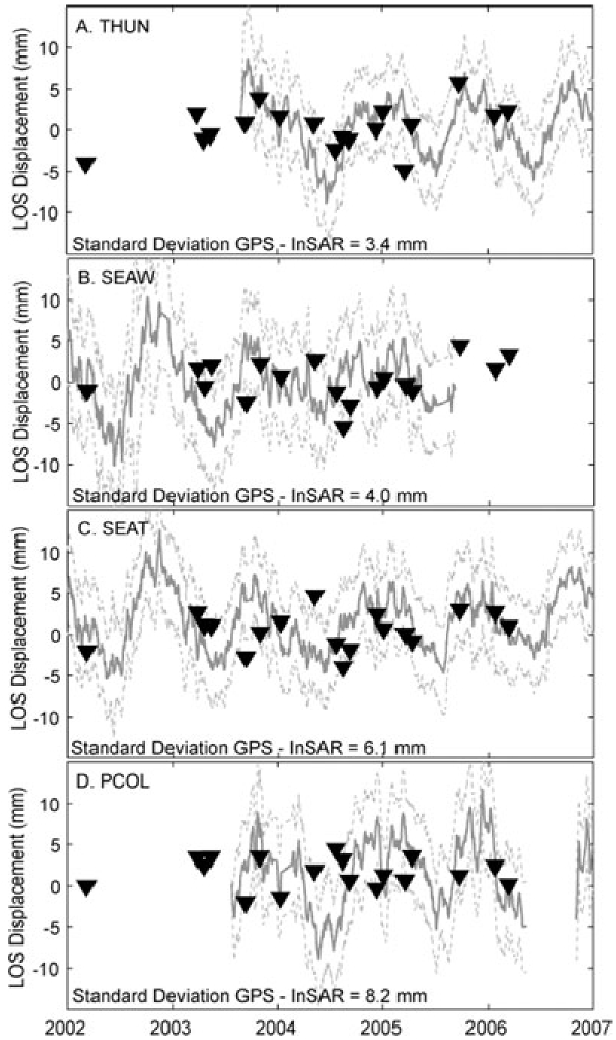


Figure 1: Comparison of LOS-projected continuous GPS data (grey line) and associated 1σ uncertainties with InSAR time series inverted from RADARSAT InSAR data (black triangles).

Examination of the InSAR observations allows us to identify whether short-wavelength non-tectonic deformation features (e.g., related to groundwater) may affect the continuous GPS records. Figure 2, taken from Finnegan et. al. [2008], shows results from ERS track 428 from 1992 to 2000. GPS station PCOL is on the southern edge of an area where the InSAR observations indicate a large seasonal deformation cycle. The standard deviation of the residual surface displacement is also higher at this point than other areas around it. Taken together, these observations highlight the possibility of some contamination at station PCOL. However, PCOL was not operational until 2003, and by that time the couplet of deformation had disappeared from the InSAR signal. The signal is most likely due to pumping from a pulp mill and gravel pit. Nevertheless, combining figures like 2(a) and 2(b) in a qualitative analysis could be a valuable tool for identifying patterns of GPS contamination and could also be used as a scouting tool for the placement of new GPS stations.

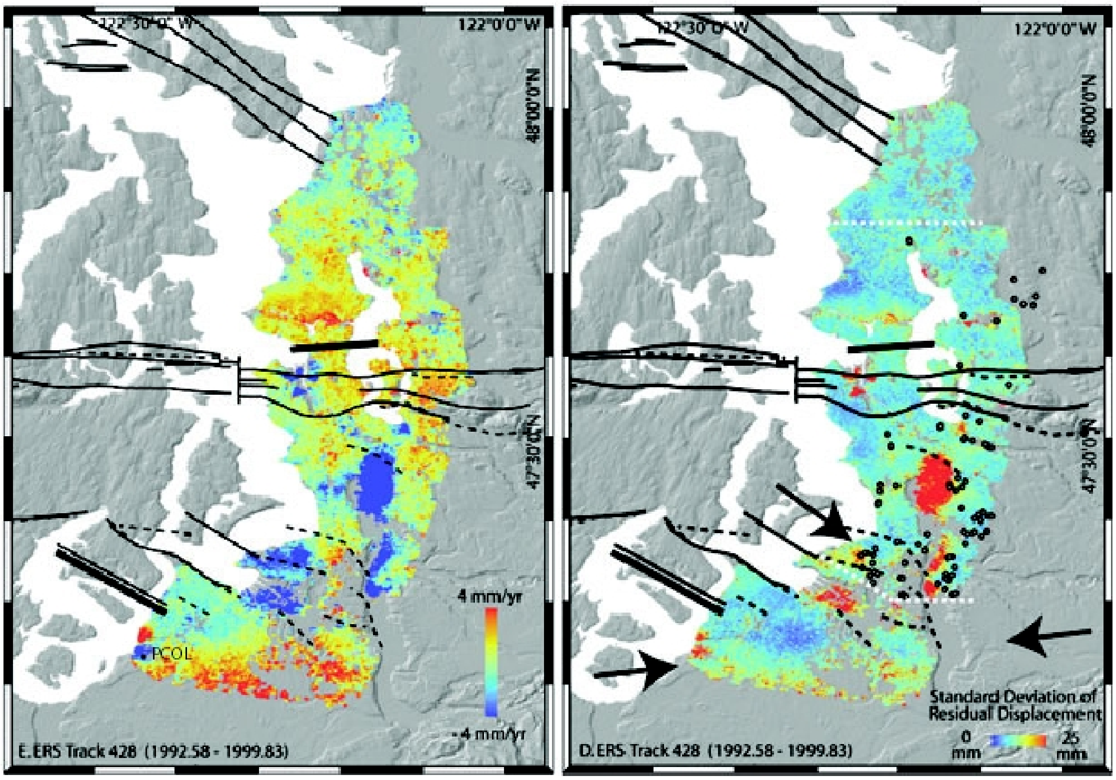


Figure 2: (a) Patterns and magnitudes of mean radar LOS surface velocity calculated from 31 ERS track 428 Interferograms. (b) Standard deviation of the residual surface displacement after subtracting the component of deformation due to the mean surface velocity.

On the timescales of the InSAR time series analyzed in this study, we expect deformation due to tectonically interesting processes, such as locking along crustal faults, to be monotonic and that processes related to groundwater or aquifers will have higher variability on these time scales. Because relative deformation in Figure 2(a) mostly corresponds well with high variability shown in Figure 2(b), we infer that most of this local deformation is driven by groundwater or aquifer activity.

C. Near-Surface Faults

Finnegan et. al. [2008] show that observed surface deformation does not seem to coincide with mapped faults or projected fault traces in the region (Figure 3). Using this null result, Finnegan et. al. calculate that locking on the thrust beneath the Seattle Uplift must occur at a depth greater than 10 km, otherwise the surface deformation due to this locking would be detectable. Alternatively, the slip deficit rate across the fault accommodating the strain could be less than the proposed maximum of ~3mm/yr with additional strain being accommodated on nearby faults. Insensitivity to longer wavelength deformation in the InSAR method prevents us from ruling out this hypothesis. Steep deformation gradients that show up in figures similar to Figure 2 could be explained as unmapped faults. Shallow groundwater processes often cause some localized deformation at fault zones, so this is a way for new faults to be discovered using InSAR.

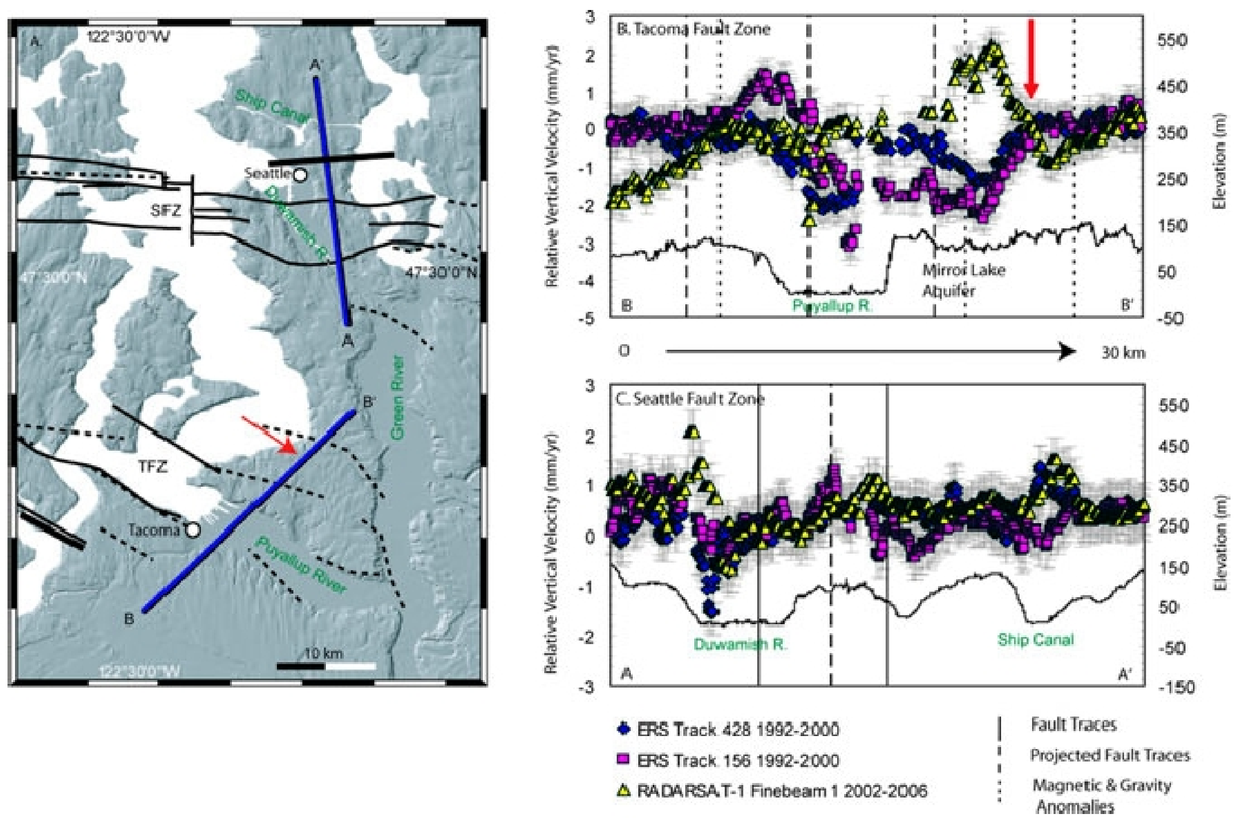


Figure 3: (a) Locations of the Seattle and Tacoma Fault zones. (b,c) InSAR derived near vertical deformation rates across these fault zones for profiles shown in (a).

D. Slow Slip Events

Identifying displacement associated with slow slip events pushes the limits of the current InSAR data archive, and although we were unsuccessful in identifying a signal, we think that further investigation may yield promising results. To begin with, we used a catalog of GPS and seismic observations of Episodic Tremor and Slip along the entire Cascadia margin compiled by Holtkamp and Brudzinski [in review, 2009] to identify the timing of ETS events from 1997 to 2008. The seismic record in southern Vancouver Island has been extended back to 1992 by analyzing analog seismograms (Herb Dragert and Garry Rogers, personal communication), so we have at least one independent constraint for the timing of events prior to 1997.

We used surface displacements measured from that compilation to set up an inversion scheme for slow slip. The Cascadia subduction interface shallows and bends from striking north-south to northwest-southeast in the northern Washington/southern Vancouver Island region. To account for this three dimensional geometry, we discretize the surface into triangles (to tile the surface without gaps) and use the elastic dislocation code of Meade [2007] to calculate Greens functions for the inversion. Figure 4a shows the results from one of these inversions (of the January 2007 event). In this inversion, most of the slip is bounded within the 30 and 40 km depth contours, consistent with published inversions of similar data and coinciding with locations of non-volcanic tremors associated with this event. There is a sizeable patch of slip updip from the 30 km depth contour, which is below the Olympic peninsula. This slip patch is primarily constrained by large displacements observed at station SC03 seated in the middle of the Olympic peninsula. Because of the rugged terrain and its location inside a national park, there are no other stations within about 50 km.

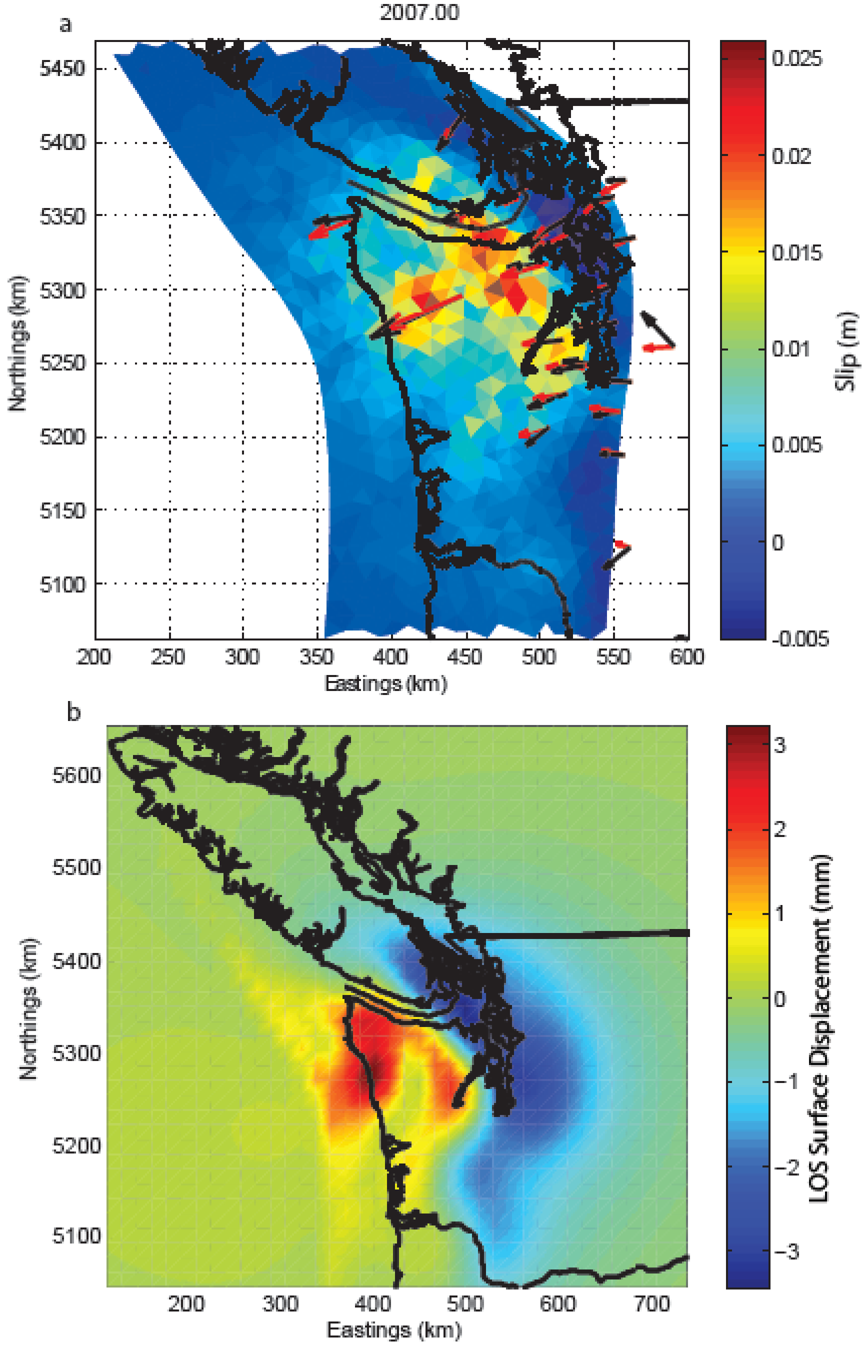


Figure 4: (a) GPS inversion of slip on the Cascadia interface. Black arrows represent observed surface displacement and red arrows represent displacements predicted from displacement pattern shown. Only the dip-slip component of the interface slip is shown. (b) RADARSAT beam S6 projected synthetic interferogram from the slip distribution shown in (a). Actual RADARSAT S6 interferogram is shown in Figure 7.

We use the slip distribution from the GPS inversion to predict the 3-D surface displacements due to slow slip events. Projecting the 3-D surface displacements into the radar satellite's line of sight (LOS) produces synthetic interferograms. Figure 4b shows the synthetic interferograms from the January 2007 event and Figure 5 shows a stack of all synthetic interferograms for the ERS LOS of slow slip events from 1997 to 2007. Only events from the northern Washington/southern Vancouver Island region are shown in this stack. Figure 5 illustrates that the Seattle urban corridor is in a poor location and orientation for recording slow slip deformation. This is because Seattle lies ~55km above the plate interface and the down dip extent of slow slip is about 40 km deep with motion during events in the up-dip direction. We see from this figure that Seattle lies in a broad zone of subsidence, whereas InSAR is most sensitive to gradients in the deformation field.

However, Figure 5 also demonstrates a key aspect that could be helpful for the detection of slow slip events. Slow slip events are fairly regular in their location (in the down dip direction) on the fault interface. This means that the deformation pattern is very similar over many slow slip cycles. This is evident in Figure 5 because the stack of 13 slow slip events still shows a relatively sharp transition from subsidence to uplift. Examination of individual synthetic interferograms confirms this spatial regularity.

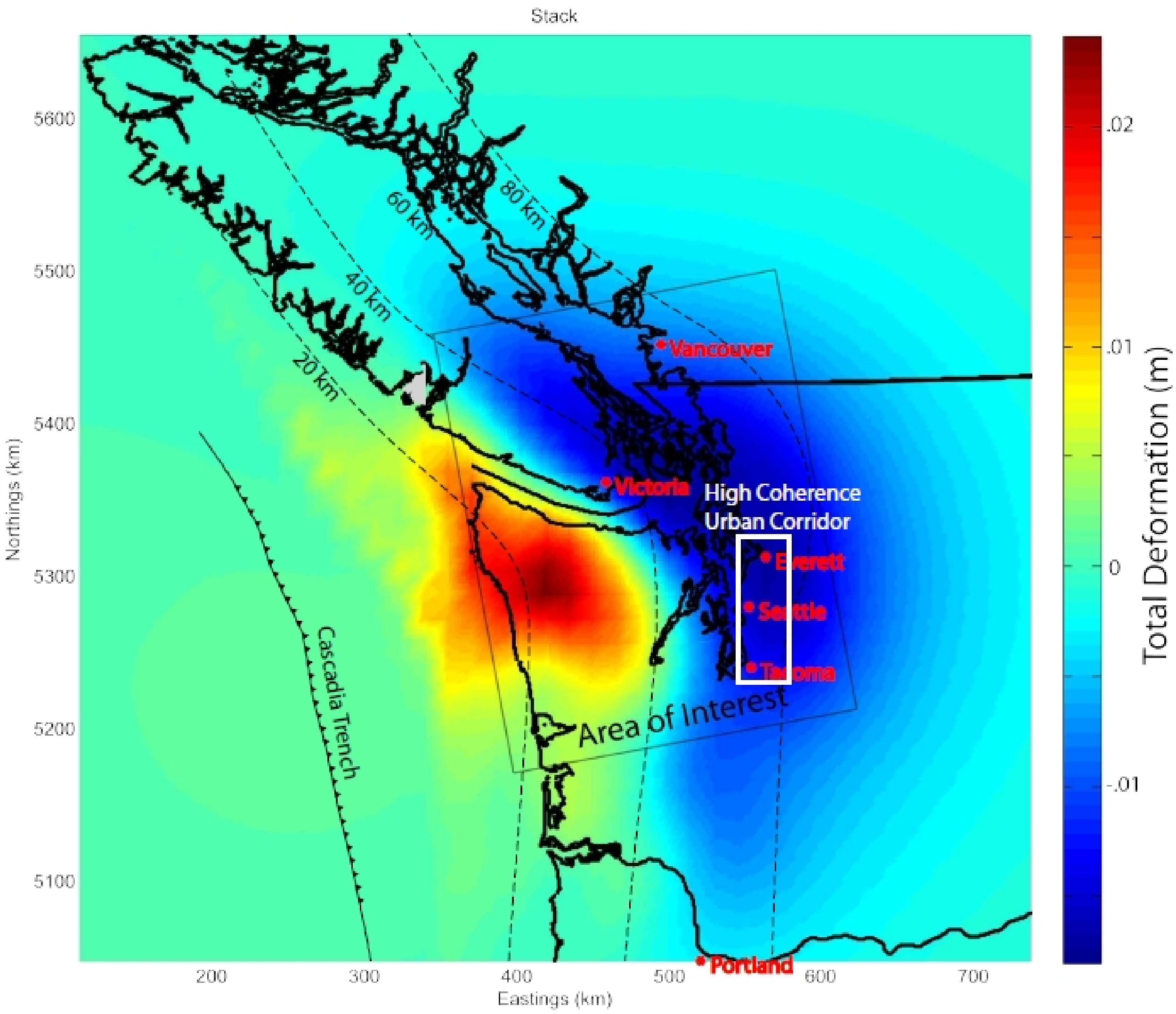


Figure 5: Cumulative surface deformation associated with all Seattle/Southern Vancouver Island slow slip events from 1997 to 2007 predicted from GPS inversions and projected into ERS line of sight. Major cities in the region are shown in red. Proposed area of interest for the Cascadia super-site is shown as black rectangle (see section F.).

We began our search for slow slip displacement using conventional two pass interferometry. We compiled a list of SAR acquisitions from the ERS 1 and 2, RADARSAT, Envisat, and ALOS satellites that spanned short time intervals and bracketed slow slip events. Short time intervals are a necessary component because this reduces the competing effects of interseismic and inter-ETS (additional deformation that is reset during a slow slip event) deformation and slow slip event deformation. Small temporal baselines also reduce the effects of temporal decorrelation. Temporal baselines were limited to 3-4 months and perpendicular baselines were limited to <~500m except for ALOS and RADARSAT Finebeam modes. Figure 6 shows the relationships between GPS and seismic observations of slow slip and tremor (small squares and triangles respectively), inferred ETS events (grey bars), and the time span of interferograms examined in this initial study (pairs of green or red lines)

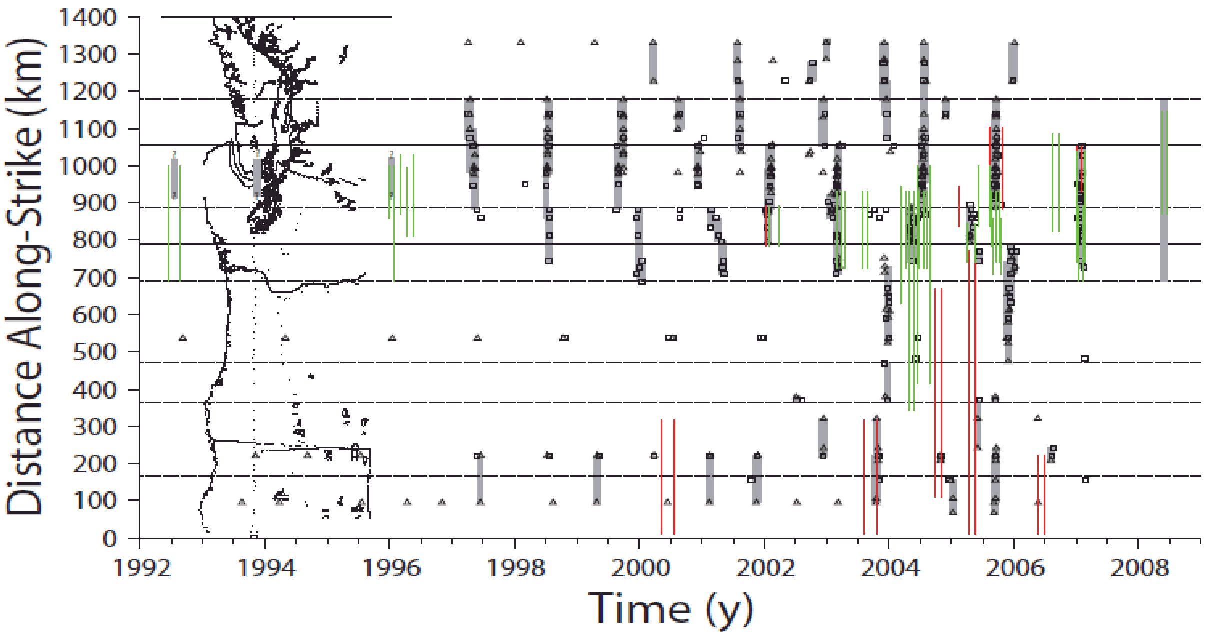


Figure 6: Summary of episodic tremor and slip (ETS) along the subduction margin determined from individual GPS (small squares) and seismic observations (triangles). Distance along-strike is from the southern end of the margin and runs along the 40 km depth-to-slab contour. The map on the left is warped to reflect distance from the 40km contour. Horizontal lines propose segmentation of the margin into groups of stations that tend to show common ETS timing. Grey bars are produced by automated code that identifies observations that are spatially and temporally coherent. Colored parallel lines show interferograms made for this study.

Scenes were acquired from ASF, directly from the European Space Agency, or the Geoearthscope data repository. Interferograms were processed using the

ROI_PAC software package maintained by JPL/Caltech. After processing, most interferograms showed long wavelength ramps due to orbit uncertainties. In these cases, quadratic ramps were removed from the unwrapped image. Unless the area the quadratic ramp is being fit to is much larger than the area of slow slip deformation, it is probable that a significant portion of the deformation signal would be mapped into the quadratic ramp that is removed. This happens because the deformation signal has a long wavelength as shown in Figures 4 and 5.

Due to the high regularity of slow slip events in space and time, it important for studies such as this that regular SAR acquisitions be made. Regular acquisitions have only been made in the Seattle region and even then only since about 2002. All of the northern Washington slow slip events since 2002 have SAR acquisitions bracketing them while none of the Oregon and only two of the northern California events do. None of the interferograms indicated in Figure 6 showed deformation that could definitely be attributed to slow slip events. Typical problems encountered included lack of coherence in the mountainous Olympic peninsula region and high short wavelength variability, which is likely to due to variations in atmospheric water vapor. Also, acquisitions have usually only been made over the Seattle region and not many acquisitions (none spanning slow slip events) have been made over the Olympic peninsula, where we would expect to find observations that place the strongest constraints on the extent of slip on the plate interface.

We investigated how interferometric coherence was related to the radar wavelength, beam mode, perpendicular baseline, and time of year. L-band (ALOS) had greater coherence regularly, but at times still had problems in mountainous regions (Figure 7d). The RADARSAT Finebeam mode did not do well in any interferograms made, while the standard beam modes at times did very well. Figure 7c shows the only interferogram with near complete coherence. It is a one month interferogram with perpendicular baseline of about 250 meters. It shows coherence in the Olympic mountain region not sampled by 7a or 7d. Time of year seemed to be an important controlling factor, with summer months having more coherence than winter months.

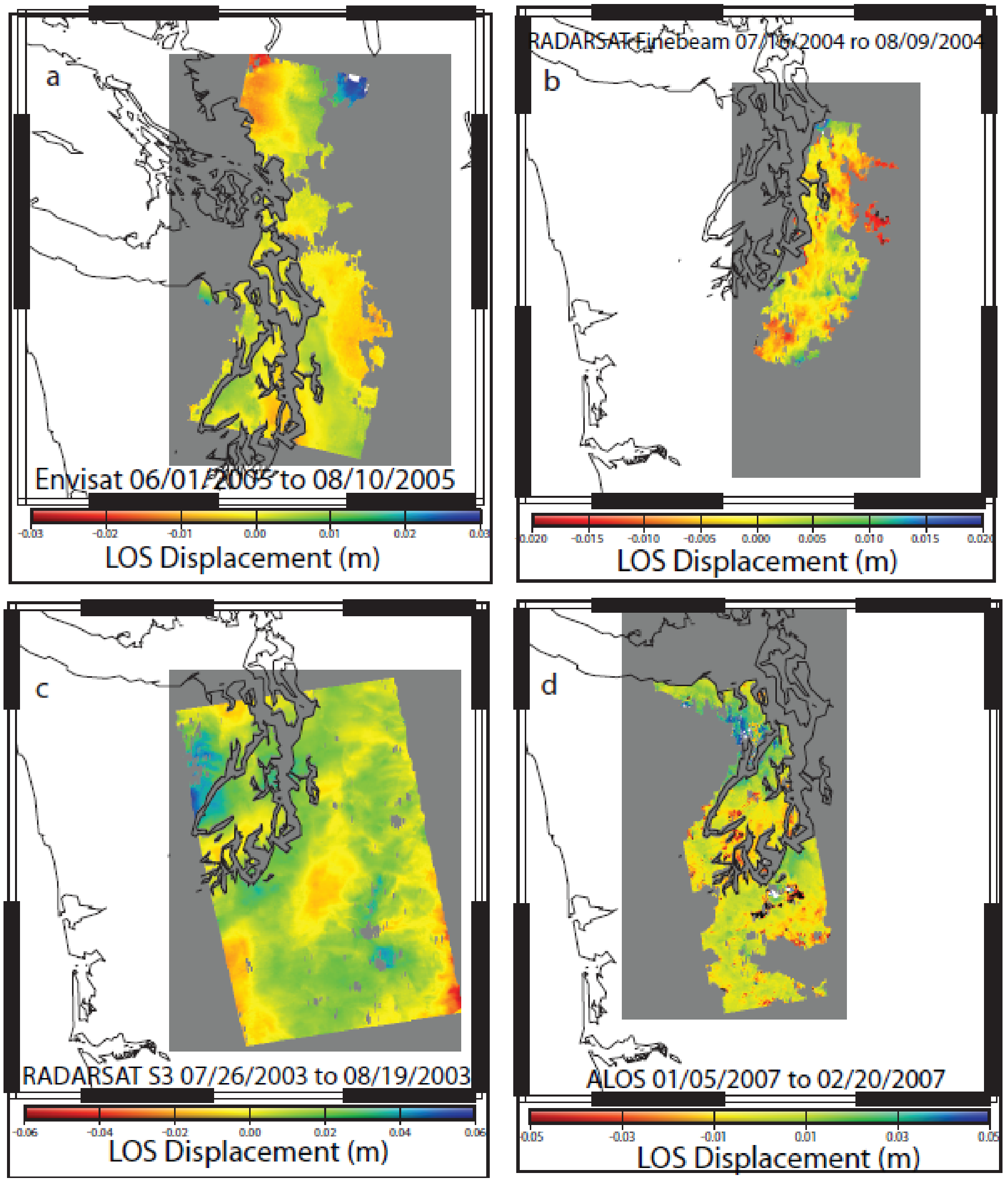
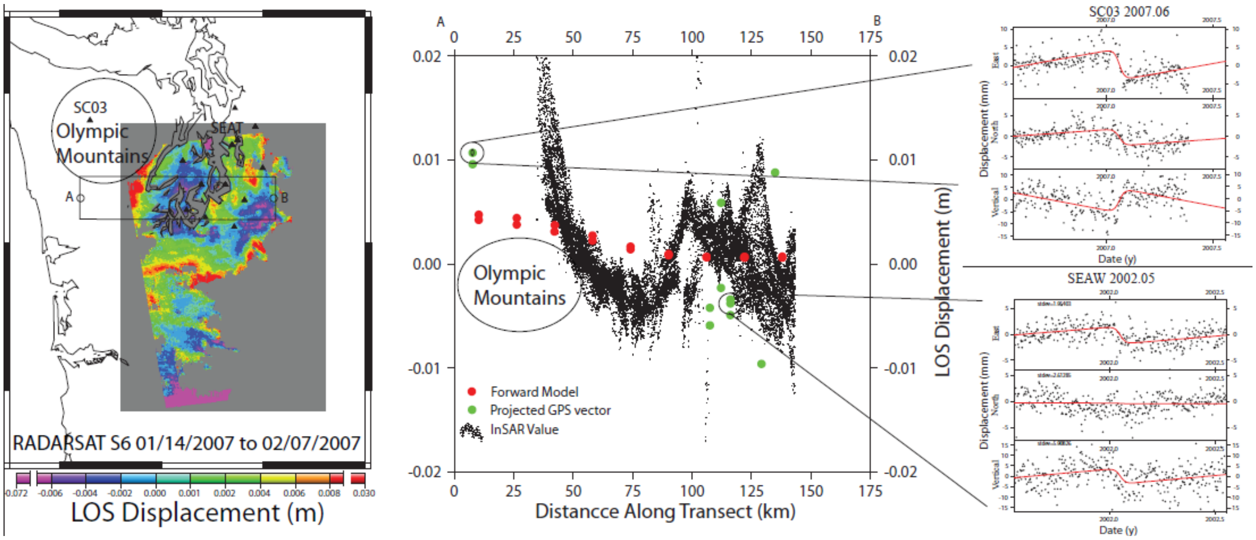


Figure 7: Representative interferograms showing areas of spatially continuous coherence and values of displacement

Figure 8 shows a sample interferogram for acquisitions spanning a slow slip event as well as comparisons along a profile to GPS observations during the same time period and deformation in the radar LOS predicted by a model inferred from the GPS. The first panel shows how the coherent region in this interferogram extends partially into the region where the change from subsidence to uplift is expected (forward model in Figure 4b). The second panel shows a 30 km wide swath transect between points A to B with relative InSAR values, GPS (projected into the radar LOS), and forward model predictions. InSAR displacements are relative to 0 mean displacement over the entire scene and therefore are not tied to the GPS values (in other words, they should be allowed to float up and down).

Figure 8: This figure compares the observed InSAR values with well constrained GPS values and the forward model predicted from the inverted GPS values.



A few key points are evident in this figure. First, large positive signal towards the west is coincident with the location of the Olympic Mountains. This type of relation is seen in several other interferograms as well, and likely reflects the well-known fact that the effects of atmospheric water vapor on interferograms is strongly related to topography. Unfortunately, as can be seen in Figures 4 and 5, the predicted deformation during slow slip events also correlates with topography. This makes it difficult to distinguish between atmospheric and deformation signals. More complicated methods of estimating and removing atmospheric signals may be useful but have not been attempted in this study.

Second, for this event and others, it appears as if the predicted surface displacement from forward models does not account for all of the LOS deformation recorded by GPS stations. Station SC03 shows this best. In two recorded events, it showed 1.0 and 1.1 cm of LOS deformation in the RADARSAT S6 line of sight, but forward models predict only 0.5 cm of deformation, despite good fits to the data in both horizontal components (Figure 4). This deficiency could be because of poor constraints on slip due to the low station density in the region or to errors in the position or orientation of the plate interface used in both the inversions and forward modeling. Observing the deformation signal with InSAR could help address both of these potential issues, but unfortunately coherence is usually lost in the mountainous Olympic peninsula. While the poor fit to forward models (which are mostly constrained by the horizontal components of the GPS) requires further explanation, the GPS data indicates that line-of-sight displacements may be as large as ~1.5cm during slow slip events, a signal level that is on par with observed signals seen in individual interferograms made in the region. This observations helps to motivate the analysis of InSAR time series, where the existence of multiple acquisitions may help separate out the competing atmospheric and tectonic signals.

E. Persistent Scatterer analysis

Results from Finnegan et. al. [2007] are only relevant for small wavelength signals within the Seattle urban corridor. As Figure 5 shows, the slow slip process is a long wavelength signal and does not have much of a gradient in deformation within the urban corridor east of the Puget Sound. Persistent scatterer techniques (e.g. Hooper et. al. 2007) have been successful at identifying pixels in regions where coherence in two pass interferometry is lost, so we apply the persistent scatterer technique of StaMPS [Hooper et. al. 2006] to our data set. Figure 9 shows mean LOS velocity output from StaMPS for each of the persistent scatterer pixels shown in a study area that encompasses part of the area studied in Finnegan et. al. and extends the analysis eastward into an area that Finnegan et. al. recovered no results. StaMPS and the time series inversion from Figure 2a produced nearly identical results in the urban corridor. Main features replicated include the large area of subsidence south of 40º30'', the lineations in the Tacoma region that line up with mapped faults, and small wavelength feature around station PCOL.

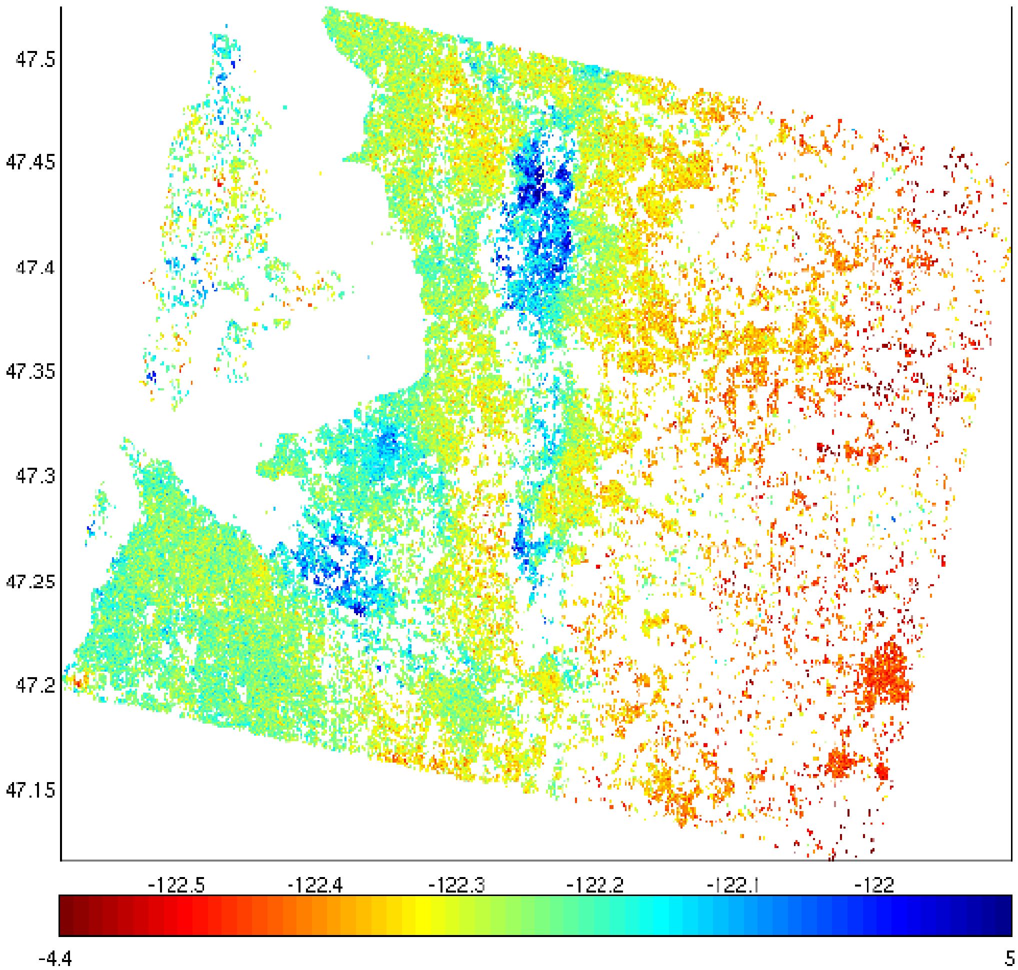


Figure 9: mean LOS velocity (comparable to Figure 2a) from persistent scatterer analysis using StaMPS

Figure 9 illustrates how persistent scatterer techniques can be applied to this region in Cascadia to extend coherence beyond the urbanized regions. Coverage is extended East of the urban corridor, but sampled areas are often not connected, making unwrapping difficult. Small baseline interferograms generally produce higher coherence, so a combined small baseline and persistent scatterer technique may help with the unwrapping issues as well as extend coverage even further.

F. The Future: A “super-site” for the Pacific Northwest

A consortium of space agencies (including NASA, the Canadian Space Agency, the European Space Agency, and the Japanese Space Agency) as well as other agencies are working together to make datasets openly available for a few areas of the world that face potential geologic hazards (e.g., earthquakes or volcanic eruptions). Because of the potential for a large earthquake in the Pacific Northwest, the Seattle-Vancouver region has been proposed to become a "super-site." This means that a large amount of InSAR data for this area (including all of the data used in our study) will become openly available. We have worked with Falk Amelung (U. Miami and Chair of the WinSAR consortium) as well as the staff of UNAVCO to define the spatial extent of the Pacific Northwest "supersite" (see the black box in Figure 5) as well as to ensure that all data used in this project will be available on the super-site. The existence of the super-site should allow other researchers to confirm and extend our work.

4. Bibliography

Publications:

Finnegan, N. J., M. E. Pritchard, R. B. Lohman, and P. R. Lundgren, Constraints on surface deformation in the Seattle, WA urban corridor from satellite radar interferometry time series analysis, Geophysical Journal International, 174, 29-41.

Presentations:

Holtkamp, S. G., M. Brudzinski, and M. Pritchard, Constraining transient vertical deformation associated with slow slip events in Cascadia.(abstract), Fall AGU 2007, T21A-0366.

Finnegan, N. J., M. E. Pritchard, R. B. Lohman, and P. R. Lundgren, Measuring vertical deformation in the Seattle, WA urban corridor with satellite radar interferometry time series analysis (abstract), Fall AGU 2007, G52A-07.

Finnegan, N. J., Constraints on surface deformation in the Seattle, WA urban corridor from satellite radar interferometry time series analysis, Geophysics seminar at the University of Washington, Feb. 2008

Holtkamp, S. G., M. Brudzinski, R. Lohman, and M. Pritchard, Vertical Deformation Associated with Slow Slip Events in Cascadia: Methods of Detection and Model Inversion (abstract), "Aseismic Slip, Non-Volcanic Tremor, and Earthquakes" Workshop in *Sidney, British Columbia, 2008.*

Finnegan, N. J., and M. E. Pritchard, InSAR time series analysis of deformation in the Seattle, WA, urban corridor and from the Socorro, NM, magma body (abstract), UNAVCO Science Workshop, Boulder, CO, 2008.

Holtkamp, S. G., M. Pritchard, R. Lohman, L. Steinberg, Searching for displacement associated with Cascadia slow slip events with InSAR (abstract), Fall AGU 2008, U33A-0019.